PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : G02B 6/28, G01B 9/02

A1

(11) International Publication Number: WO 93/03406

(43) International Publication Date: 18 February 1993 (18.02.93)

(21) International Application Number: PCT/AU92/00422

(22) International Filing Date: 10 August 1992 (10.08.92)

(30) Priority data:

PK 7673	9 August 1991 (09.08.91)	AU
PL 1391	17 March 1992 (17.03.92)	AU

(71) Applicant *(for all designated States except US)*: AUSTRALIAN AND OVERSEAS TELECOMMUNICATIONS CORPORATION LIMITED [AU/AU]; 231 Elizabeth Street, Sydney, NSW 2000 (AU).

(72) Inventor; and

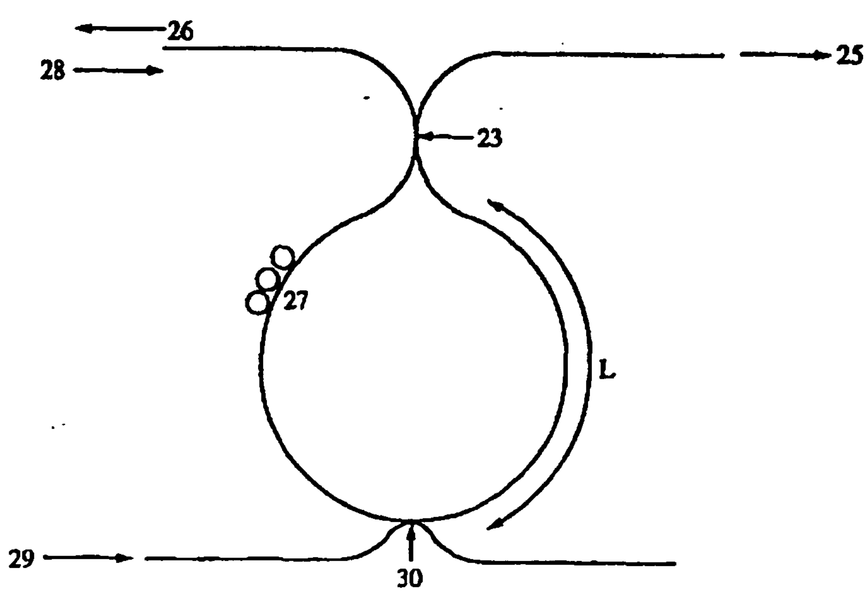
(75) Inventor/Applicant *(for US only)*: BETTS, Ralph, Alexander [AU/AU]; 39 Oberon Street, Randwick, NSW 2031 (AU).

(74) Agent: WATERMARK PATENT & TRADEMARK ATTORNEYS; Level 4, Amory Gardens, 2 Cavill Avenue, Ashfield, NSW 2131 (AU).

(81) Designated States: AT, AU, BB, BG, BR, CA, CH, CS, DE, DK, ES, FI, GB, HU, JP, KP, KR, LK, LU, MG, MN, MW, NL, NO, PL, RO, RU, SD, SE, US, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, SN, TD, TG).

Published
With international search report.

(54) Title: SAGNAC LOOP GATES



(57) Abstract

A three terminal optical device (26, 25, 30) is disclosed based on a Sagnac interferometer. Control pulses (29) are coupled into the Sagnac loop (L) which switch the system from transmission to reflection. The control pulses preferably have a different wavelength from the signal, allowing their separation by suitable means for separating different wavelengths. Applications are described for signal routing, unchirped pulse generation, autocorrelation and signal sampling.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria
AU	Australia
BB	Barbados
BE	Belgium
BF	Burkina Faso
BG	Bulgaria
BJ	Benin
BR	Brazil
CA	Canada
CF	Central African Republic
CG	Congo
CH	Switzerland
CI	Côte d'Ivoire
CM	Cameroon
CS	Czechoslovakia
CZ	Czech Republic
DE	Germany
DK	Denmark
ES	Spain
FI	Finland
FR	France
GA	Gabon
GB	United Kingdom
GN	Guinea
GR	Greece
HU	Hungary
IE	Ireland
IT	Italy
JP	Japan
KP	Democratic People's Republic of Korea
KR	Republic of Korea
LI	Liechtenstein
LK	Sri Lanka
LU	Luxembourg
MC	Monaco
MG	Madagascar
ML	Mali
MN	Mongolia
MR	Mauritania
MW	Malawi
NL	Netherlands
NO	Norway
NZ	New Zealand
PL	Poland
PT	Portugal
RO	Romania
RU	Russian Federation
SD	Sudan
SE	Sweden
SK	Slovak Republic
SN	Senegal
SU	Soviet Union
TD	Chad
TG	Togo
UA	Ukraine
US	United States of America

SAGNAC LOOP GATES

TECHNICAL FIELD

This invention relates to optical sampling or gating, to means and methods for optical sampling or gating and to devices utilising such means and methods. The invention also relates to high speed optical waveform capture using such devices together with pulsed lasers, and to applications of these devices and methods.

BACKGROUND ART

In the acquisition of electrical or optical waveforms, it is important to be able to sample or gate an electrical or optical signal in a very short period. This is traditionally achieved for electrical waveforms using fast electronic switches or gates such as transistors. In the case of optical waveforms, this is usually achieved by detection with a high bandwidth photodiode and electronically sampling the resulting electrical waveform.

Sampling of optical waveforms

Optical waveforms are time varying optical signals, such as a beam of light, the power of which varies as a function of time. There are a large number of ways in which such signals can be produced, some of which result in signals which vary very rapidly. Two methods have traditionally been used to measure such waveforms.

Optical photodiode head and electronic sampling

The simplest way to measure optical waveforms is to detect the waveform using a fast optical detector and to sample the resulting signal electronically. The limitations to such a scheme are the bandwidth of the photodetector and electronic amplification stages and the sampling "window" of the electronic sampler / gate. The best currently available instruments are bandwidth limited to about 60GHz (approximately 7ps time resolution).

Electro-optic sampling

An alternative to the above scheme is the method known as electro-optic sampling. Again, a fast optical detector is required - however, in this case the resulting electrical waveform is electro-optically sampled rather than electronically sampled. This reduces the sampling window to a value approximately equal to the optical pulse duration (<1ps), although the photodiode bandwidth still limits the measurement bandwidth to about 60GHz.

Electro-optic sampling has been found particularly suitable for the characterisation of fast photodiodes. The method uses a high speed electro-optic modulator and ultra-short laser pulses produced, for example by a modelocked laser. The optical pulses are split into two beams - one is incident on the photodetector and the other, which is subject to a variable time delay, is incident on the electro-optic modulator. The voltage generated by the photodetector is the electrical input to the modulator. The optical pulses effectively sample

the voltage at the exact time they are subject to modulation, as the average optical power out of the modulator is directly related to the electrical signal voltage at the sampling instant. This time can be varied using the variable time delay - this gives the impulse response of the photodiode.

Sagnac Loop Interferometer Switches

A Sagnac loop interferometer is a non-resonant interferometer in which light can propagate in both directions around a common physical path before recombination. Under normal conditions the light will exit along the input path (ie. will be reflected). However, if by some mechanism the optical path in one direction can be made different to that in the opposite direction, light can be transmitted. If the difference in phase change between the clockwise path and the anticlockwise path is $\Delta\phi$, the transmission coefficient is given by $T = \sin^2\Delta\phi$. This can be achieved if the material in the loop is nonlinear (ie. the refractive index is a function of optical intensity), the input light is in the form of short pulses (much shorter than the loop length) and the counterpropagating pulses have different powers. The device is now an intensity dependent switch (light will either be reflected or transmitted depending on its intensity).

Bulk configuration

Prior Art Figure 1 (a) shows a Sagnac loop interferometer constructed from bulk components. Light is incident at point 4 and impinges upon a beam splitter 1 where it is split equally. It is then reflected from mirrors 2 and 3 and again impinges upon the beamsplitter 1. Light exits at points 4 and 5. If the alignment is perfect, there is an on-axis maximum in the fringe pattern at point 4 and a minimum at point 5 - this corresponds to reflection. Such bulk devices have found application as optical gyroscopes.

All fibre configuration

The all fibre Sagnac loop interferometer is represented in Prior Art figure 1 (b). Light is incident at point 11. The light is split by a fused tapered optical fibre coupler 17 and the loop is simply a length of fibre 13. Light exits from point 19 (reflection) or point 15 (transmission). A polarisation controller 18 can be included in the loop. This can be used to tune the operating point of the device - by varying the adjustment of the polarisation controller the loop can be made completely reflecting, completely transmitting or partially transmitting as desired.

Since standard silica fibre is slightly nonlinear, this device will operate as a switch for pulsed light if the pulses have sufficiently short duration and high power and the coupler is not a 50% coupler (this introduces an asymmetry into the loop - ie. different power

pulses travel in opposite directions). An alternative method to introduce asymmetry is to include an optical amplifier at the start or end of the loop - this results in very low switching powers due to the high gains available.

Optical sampling of optical signals using a Sagnac loop has been reported [B.P.Nelson and N.J.Doran, Electronics Letters, 27, 3, pp204-5 (1990)] using a wavelength dependent coupler having a 50% split ratio at the signal wavelength and a 100% split ratio at the sampling wavelength - the sampling wavelength travels only one direction around the loop. This scheme is severely limited by the fact that the coupler must be specially selected and after selection will only work satisfactorily for one signal wavelength and one sample wavelength.

A paper by H. Avramopoulos et al [IEEE Photonics Technology Letters, Vol 3, No3, pp 235-237 March 1991] discloses a 3 terminal sagnac switch using polarisation to separate the sampling pulses from the signal.

DISCLOSURE OF INVENTION

According to one aspect the present invention provides an improved optical sampling device comprising an optical fibre Sagnac interferometer comprising first coupling means having an input port, an output port, an optical loop joining two other ports of said first coupling means, and a second coupling means intermediate the loop , the arrangement being such that a signal is produced on said output only when a signal is input having a first wavelength, and a control pulse is input to said loop having a second wavelength through said second coupling means.

According to another aspect the present invention provides an optical pulse generator comprising a first optical coupling means having an input for receiving a CW signal , an output, and a loop of optical fibre connecting two ports of the first coupling means so as to form a Sagnac interferometer, said loop further including a second optical coupling means connected to a pulsed optical source , the arrangement being such that said output produces unchirped optical pulses .

According to a further aspect the present invention provides an optical routing device comprising an optical fibre Sagnac interferometer comprising first coupling means having an input port, a first output port including part of the same optical path as said input port, and a second output port, an optical loop joining two other ports of said first coupling means, and a second coupling means intermediate the loop , the arrangement being such that an input signal having a first wavelength is routed to one of said output ports only when a control pulse having a second wavelength is input to said loop through said coupling means, and the input signal is otherwise routed to the other of said

output ports .

BRIEF DESCRIPTION OF DRAWINGS

The invention will now be described in more detail with reference to the drawings, in which:

Figure 1(a) illustrates a bulk optics implementation of a Sagnac Loop;

Figure 1(b) illustrates a fibre implementation of a Sagnac Loop;

Figure 2(a) illustrates one embodiment of a sampling arrangement according to the present invention;

Figure 2(b) is a schematic diagram of the function of the embodiment of Figure 2(a);

Figure 3 illustrates one embodiment of a sampling system using the inventive sampling arrangement;

Figure 4 illustrates one embodiment of another sampling system using the inventive sampling arrangement;

Figure 5 illustrates a further system embodying the inventive sampling arrangement;

Figure 6(a) illustrates a system for pulse generation and/or signal routing using the inventive sampling arrangement;

Figure 6(b) is a schematic diagram showing the function of the embodiment of Figure 6(a);

Figure 7 illustrates a passively modelocked laser system;

Figure 8 is a schematic diagram of a system for generating unchirped pulses according to the present invention;

Figure 9(a) illustrates a further embodiment of the inventive sampling arrangement utilising polarisation maintaining components;

Figure 10 shows a system according to the present invention for generating dark pulses;

Figure 11 shows an all fibre autocorrelator according to a further embodiment of the present invention;

Figure 12 illustrates the launched pulse waveform according to the second example;

Figures 13(a) and 13(b) illustrate received pulse waveforms after different distances according to the second example;

Figure 14 is a schematic diagram of an experimental arrangement allowing for loop recirculation;

Figure 15 illustrates the initial pulse waveform according to a first example;

Figures 16(a) and 16(b) show a typical output pulse and dark pulse according to the first example respectively; and

Figure 17 shows the optical spectrum of the output pulses according to the first example.

DETAILED DESCRIPTION

The present invention relates to an arrangement whereby an additional coupler is introduced to a Sagnac loop, to allow the introduction of a gating or sampling pulse.

This configuration acts as a sampler or gate and is represented in figure 2 (a). In this device the signal is incident at point 28 and enters the Sagnac loop at the 50% coupler 23. It is then split and travels both directions around the loop and exits at point 25 or 26 depending on the relative phase of the recombining light as described in relation to the Sagnac loop. Also included in the loop is an additional coupler 30, which allows a sampling or gating pulse 29 to enter the loop - this travels only one direction (anticlockwise) around the loop. This coupler should ideally be located exactly half way round the loop to avoid introducing an asymmetry into the loop in the absence of a sampling signal but this is not essential. In order to allow operation over a large range of signal and sample wavelengths, broadband "wavelength flattened" 50% couplers would be appropriate at 23 and 30, however this is not essential. Polarisation controller 27 may be included.

Figure 2 (b) shows the device in schematic form. Light incident at port 31 will be output from port 35 in the presence of a control signal at port 32 - in other words, the signal is only sampled when a control signal is present at port 32.

If short, high power pulses (eg. 20W peak power, 1ps duration - typical of modelocked fibre lasers as discussed below) are used as sampling pulses, then10W will be coupled into the loop. We also assume that the signal power is much lower than the sampling pulse peak power (say less than 10mW). The difference in phase between the recombining low power signal, $\Delta\phi$ is given by:

$$\Delta\phi = k_0 \Delta n L = \frac{2\pi n_2 P L}{\lambda A_{eff}}$$

where $k_0=2\pi/\lambda$ is the free space propagation coefficient at wavelength λ, $\Delta n = n_2 P/A_{eff}$ is the nonlinear change in refractive index, n_2 is the nonlinear refractive index of the loop fibre, P is the sampling pulse power, L is the length of the loop in which both signal and control are present(between coupler 23 and coupler 30) and A_{eff} is the effective area of the loop fibre.

For half switching (ie. switching from complete reflection to complete transmission) we require $\Delta\phi=\pi$.

We then have:

$$L = \frac{A_{eff}\,\lambda}{2n_2P}$$

For typical fibre parameters this gives a length of about 60m for half switching. For specially designed fibres with high n_2 and small A_{eff} this could be reduced by a factor of 10 to 100 - possibly more with new highly nonlinear fibres. In integrated optics form, using highly nonlinear materials this length could be reduced by four orders of magnitude or more making such devices suitable for implementation on standard size chips (a few cm^2).

It should be clear from the above that this device is an optical sampler or gate which is normally reflective in the absence of a sampling or gating signal, but when appropriately configured becomes transmissive when a sampling or gating signal is present. This device is essentially analogous to a field effect transistor (FET) configured as an electronic switch or gate.

A major advantage of the Sagnac Loop Gate is speed - the Kerr effect has a response time of the order of femtoseconds in materials such as silica therefore such gates can be ultra-fast. The gating speed limitations are the minimum duration gating pulses that can be produced (< 100fs) and the degree of walk-off in the loop of the sample pulse and the signal. For a 10m loop of fibre with a typical dispersion of 15ps/(nm.km) the walk-off could be as much as 5ps for a signal at 1500nm and sampling at 1536nm - however this walk-off could be reduced to less than 100fs by using dispersion flattened fibre. These considerations suggest that such devices could potentially have bandwidths in excess of 10THz (10000GHz) by comparison with 60GHz achievable with current "state of the art" electronic sampling devices.

Pulsed lasers

In order to make use of the huge bandwidth of the SLG, it is necessary to have extremely short, high power pulses of light to act as the sampling pulses. There are a number of known means to generate such pulses. Two suitable sources of such pulses are described below - the gain switched semiconductor laser and the modelocked laser.

Gain switched semiconductor lasers

Semiconductor lasers are available with a wide range of emission wavelengths. Short pulses can be produced using such lasers by supplying them with short pulses of current using, for example step-recovery diodes - the output light pulses can be considerably shorter than the pulses of current since it takes a period of time for the population to invert

giving overall gain (greater than loss). If the current pulse ends very shortly after overall gain has been achieved laser output will only result for this much shorter period of time. Pulses of a few mW peak power with a few tens of ps duration can be achieved using this method. Optical amplification is generally necessary to obtain sufficiently high power pulses.

Modelocked lasers

An alternative method for producing short optical pulses is modelocking of lasers. There are two forms of modelocking - active and passive.

In active modelocking a phase or amplitude modulator is located within the laser cavity and is operated at the fundamental frequency of the cavity (= 1/(round trip time)) or at a harmonic of this frequency. This has the effect of causing the longitudinal modes within the gain bandwidth of the laser gain medium to "lock" in phase. This has the result that the output becomes a pulse train with a repetition rate equal to the modulation frequency. Pulse duration, Δt that is "transform limited" can be achieved ie

$$\Delta t = 0.44 / \Delta v$$

where Δv is the gain bandwidth (this assumes a Gaussian pulse shape). Actively modelocked lasers have produced pulse durations of less than 1ps.

In passive modelocking an element with a nonlinear transmission is included in the laser cavity. The element should have a transmission which increases with increasing input power. This element can be for example a saturable absorber or a Sagnac loop. This causes pulses within the loop to increase in peak power and to reduce in duration until limited by the gain bandwidth of the gain medium. Such lasers can give kW pulses with durations of a few tens of fs. Probably the most suitable laser of this type for use with the SLG is the soliton figure of eight Erbium doped fibre laser [AOTC Ltd.,Modelocked lasers, PCT/AU92/00093]. This type of device can produce pulses with peak powers greater than 50W and durations of a few hundred femtoseconds.

Figure 7 illustrates one embodiment of a Sagnac loop passively modelocked laser, incorporating optical amplifier 12, non-linear fibres 14 and 22, couplers 10 and 40, isolators 20, 21 and attenuator 24. The operation of this configuration is described in more detail in the above referenced PCT/AU/00093, the disclosure of which is hereby incorporated by reference.

Sampling of triggered optical signals

If the optical event of interest can be triggered by the sampling pulses then the SLG can be used in a straightforward manner to measure the optical power as a function of time for the event. Methods to achieve this are described below.

Variable delay line implementation

One embodiment of a sampling system based on the SLG is depicted in figure 3. High

peak power, short duration pulses (eg. 10W, 1ps, 1MHz repetition rate, 1536nm wavelength) are incident at point 41. The coupler 42 cross couples about 3% of the power which is used to trigger a high speed optical "event" eg. the production of gain switched semiconductor laser pulses. These semiconductor laser pulses are then modulated at a low frequency compared with the repetition frequency by a mechanical chopper or electro-optic modulator 44 and are then incident into the Sagnac loop via coupler 45. The Sagnac loop is tuned to be 100% reflective in the absence of sampling pulses into the loop using polarisation controllers 46 and 47. The pulses from the other arm of coupler 42 are first passed through a variable optical delay line 48 and are then inserted into the loop through coupler 49. These pulses sample the signal as described previously causing the loop to become transmissive. The transmitted signal is detected using a photodiode receiver and a tuned amplifier 50 (tuned to the modulation frequency). The point of sampling can be varied using the variable delay line enabling the signal to be traced out in time with ultra-short time resolution.

Swept sampling instant implementation

One alternative to the above scheme is to trigger the optical event at a slightly different frequency to the repetition frequency of the sampling pulses. This scheme is outlined in figure 4. The arrangement is similar to figure 3 except that the variable optical delay line 48 is no longer required and the trigger frequency is slightly increased 54 before triggering the repetitive optical signal. This effectively sweeps the sampling pulses through the signal event. It is important to ensure that the sweep rate is sufficiently slow that the tuned amplifier can track the signal level variations.

Random sampling instant implementation

If it is inconvenient to trigger the optical event to be measured, a technique known as random sampling which is used in oscilloscopes can be used. The optical signal must be repetitive. A trigger clock is extracted from the signal using conventional techniques. The sample pulses typically have a much lower repetition frequency than the signal. These sample pulses, not being synchronised to the signal occur at what are essentially random times with respect to the trigger clock. If the delay between each sample pulse and the next trigger clock pulse is measured electronically and the detector is fast enough to measure the signal output power for each individual sample then the signal waveform can be reconstructed from this information. This method however can only be as accurate as the electronic timing and is currently limited to a few GHz.

Swept sampling of arbitrary input signals

The ideal in time domain repetitive optical signal measurement is to measure

arbitrary input signals. Theoretically this is fairly straightforward since all that is necessary is to lock the sampling pulse repetition rate to an appropriate clock (either externally supplied or internally derived). Then a scheme such as that described above as swept sampling instant implementation could be used. Practically this requires that the pulse source laser have an externally controllable variable repetition rate. Control of pulse repetition rate in actively modelocked lasers can be achieved by driving the modulator at the required frequency and varying the cavity length until satisfactory pulsed output is achieved at the required frequency. A feedback loop may be used to stabilise this output. Control of repetition frequency in passively modelocked lasers is likely to be more difficult but still possible using similar techniques.

Figure 5 shows how an arbitrary repetitive optical waveform could be measured in this way. The signal is incident at point 51 and a small fraction of the signal (say 5%) is coupled out at coupler 52 into a photodiode receiver 55. A trigger clock is then extracted using conventional oscilloscope techniques and its frequency is shifted down slightly. This resulting clock is then used to control the repetition rate of a modelocked laser 56. This pulse train is then used as the sampling train incident at coupler 57. The signal from the other arm of coupler 52 is modulated using modulator 53 and is incident on the Sagnac loop gate at coupler 54. The output signal is detected by photoreceiver 58 and tuned amplifier 59.

Pulse / dark pulse generation and signal routing using Sagnac loop gate

One application of the SLG is to produce unchirped short pulses or "dark pulses" over a wide range of wavelengths. The operation is simple. Figure 6 (a) shows a Sagnac loop gate operating in this way. The input at point 61 is continuous wave (CW) light at the required wavelength. The input into arm 63 is the output from a pulsed laser having pulses of the required duration and repetition rate, which are inserted into the loop via coupler 64. If the Sagnac loop gate is tuned for maximum reflection using polarisation controllers 67 and 68 in the absence of control pulses, the output from the Sagnac loop gate at point 65 is half the power of the control pulses coupled into the loop plus signal pulses of similar duration. Since these have different wavelengths they may be split into two outputs 69, 70 using an appropriate WDM coupler 66 (any form of optical filter with the appropriate characteristics could also be used). Such pulses may be amplified by an optical amplifier if required to form solitons.

"Dark pulses" are short periods of no light in a beam which otherwise has constant power. Such a signal will be reflected by the SLG and can be extracted using a coupler 72 or a known optical circulator in the input arm. Reflected signal pulses then exit from output 71. Alternatively, if the SLG is initially tuned for maximum transmission, then dark pulses will

result from the output 69.

Figure 6 (b) shows the device in schematic form. Light incident at port 75 is routed to port 77 or port 78 depending on the power of a control signal incident at port 73.

A preferred configuration for signal routing is to use an optical circulator 80 instead of the input coupler as shown in figure 10. A circulator 80 is a three (or more)port device which operates like an isolator for the forward path (the input) but light returning from the Sagnac loop (the reflected output "out 1") is routed to a third port.This overcomes the intrinsic losses for both forward and return paths associated with a coupler (the circulator has only a small excess loss, ≈ 0.5 dB,for both paths). Filters 79, 74 prevent the transmission of pulse at the control pulse wavelength. This arrangement can also be the basis for optical routing and optical logic as described below. A preferred optical circulator is shown in co-pending Australian patent application No PL1713 by the present applicant.

Unchirped Optical Pulse Generator

The generation of unchirped optical pulses (ie. transform limited) from chirped pulses, produced for instance by laser diodes by the known technique of gain switching is an important telecommunications application of the present invention. The envisaged applications are for low chirp, return to zero (RZ) transmission to maximise the transmission length of dispersion limited systems (linear transmission) and the generation of transform limited optical pulses which are suitable for transmission as solitons (nonlinear transmission). The use of an SLG according to the present invention provides a more elegant and flexible solution than existing schemes.

One known technique uses actively modelocked lasers and external modulators to generate solitons. This imposes the wavelength and repetition rate of the modelocked laser on the system and requires a balanced Mach-Zehnder interferometric modulator (these are expensive and typically have high loss (≈ 5dB)). Another existing scheme uses gain switched lasers and complex spectral shaping. However this method at best produces pulses that are only close to transform limited and the quality of the pulses can vary considerably over time

The inventive SLG enables a technique for unchirped pulse generation which does not exhibit the difficulties of prior art devices.

Referring to figure 8,this configuration is broadly similar to that shown in figure 6 , however,the input signal coupler is omitted (the reflected signal is not required) and the control pulse coupler 81 is not half way round the loop since the signal power into the loop (approximately 1mW) causes negligible nonlinear switching due to the asymmetry of the loop. This reduces the overall loop loss by the loss of the nonlinear fibre omitted. The output filter 82 is preferably a fibre-pigtailed, tunable,dielectric, bandpass filter. This has the

practical advantages of being easily tunable, having a single narrow passband and having excellent out of band suppression (necessary to remove the control pulses). In figure 8, some details of the signal and control pulse generation are included. The signal is a CW DFB laser diode 84 with a fibre pigtailed isolator 85 on the output. The control(switching) pulses are gain switched pulses from a DFB laser diode 86 which are amplified by an Erbium doped fibre amplifier (EDFA) 88. The configuration illustrated in figure 8 also includes an output amplifier 87 to boost the output pulse power to suitable levels for either linear or nonlinear (soliton)transmission.

Example

Two practical examples of the present invention will now be described. It will be noted that this is by way of illustration only and is not intended to be limitative of the scope of the invention.

First example

The pulse generator configuration used is shown in figure 8. The signal source was a 1544nm DFB laser diode 84 which was current tunable through ±0.9nm. The output from this laser passed through a fibre pigtailed polarisation independent isolator 85 and into the Sagnac loop through a wavelength flattened 50% fibre coupler 62. The power into the Sagnac loop from the signal laser was 0.6mW. The Sagnac loop contained a further coupler 81 to combine the signal and the control pulses, 12.6km of dispersion shifted fibre 83 (dispersion zero at 1547nm) and a polarisation controller 68. The overall loss of the loop when tuned for maximum transmission using the polarisation controller was 12.4dB. The output of the Sagnac loop was passed through a tunable 3nm bandpass dielectric filter 82 to remove the control pulses and a fibre amplifier 87 to amplify the pulses to a level suitable for transmission (>1mW).

The control pulses were generated using a DFB laser diode 86 which was gain switched using electrical pulses of 220ps duration and 2V amplitude direct from a 3Gbit/s bit error rate test set (BERT). This produced optical pulses with a measured duration of ~60ps and a peak power of 1.0mW at 1533.4nm. The pulse waveform and spectrum of these pulses after amplification are shown in Figure 15. The pulses produced by this laser were then amplified using an erbium doped fibre amplifier (EDFA) 88 with a saturation output power of 8 dBm and combined with the signal in the Sagnac loop using the second coupler 81 mentioned above. At low repetition rates (<20MHz), the peak output power of the pulses was 700mW (launching 500mW into the loop).

The device worked well as an optical gate. The loop was first tuned to have minimum

transmission in the absence of control pulses (>20dB extinction was achieved). When the control pulses were introduced into the loop, output pulses at the signal wavelength were observed having a similar duration to the control pulses. Figure 16(a) shows a typical output pulse after amplification. The duration is 57ps which is very close to the duration of the control pulses. The peak power observed was 1.5mW. 'Dark' pulses could also be produced by tuning the loop for transmission in the absence of control pulses (see Figure 16(b). It was found that at low repetition rates 'overswitching' could occur causing a 'valley' in the middle of the pulse or sometimes two pulses, and at high repetition rates incomplete switching occurred resulting in a pulse with reduced amplitude but also reduced duration. This occurs because the peak power of the control pulses reduced with repetition rate as the input amplifier saturates. As a result, the gate causes incomplete switching and the transmission characteristic is one which gives increasing transmission with increasing input power: a pulse duration compressing characteristic. Compression factors down to 0.7 were observed. Pseudo-random data was generated in this manner at bit rates up to 1.2 Gbit/s with peak power up to 1mW.

The spectrum of the output pulses was measured using a scanning Fabry-Perot interferometer with a 1nm free spectral range and a finesse of 50. The measured optical spectrum is shown in Figure 17(i). This spectrum contains a component caused by the pulses and a CW component (caused by the incomplete extinction of the Sagnac loop). Figure 17(iii) shows the spectrum with the control pulses absent (the CW only) and Figure 17(ii) shows the spectrum of the pulses only, found by subtracting trace (i) from trace (iii). The 3dB bandwidth of the pulses (taking the resolution of the Fabry-Perot into account) is 8.7GHz. The measured duration of the pulses was 57ps using an oscilloscope with an impulse response of 25ps. The actual duration of the pulses is therefore ~51ps giving a time-bandwidth product of 0.44 indicating that the output pulses are near transform limited.

Improvements in fibre nonlinearity and amplifier saturation will enable further reduction of the loop length which will reduce the loop loss and the sensitivity to vibration. Also, if complete switching is not required because the output amplifier can compensate for the reduced power, the loop length can be still further reduced; a loop length of a few hundred metres could be sufficient. A further benefit in using incomplete switching is that advantage can be taken of pulse compression.

Second Example

A further example also uses the configuration shown in figure 8. The signal source was a 1554nm DFB laser diode 84. The output from this laser passed through a fibre pigtailed polarisation independent isolator 85 and into the Sagnac loop through a wavelength

flattened 50% fibre coupler 62. The power into the Sagnac loop from the signal laser was 0.8mW. The Sagnac loop contained a further 70% coupler 81 to combine the signal and control pulses, 12.6km of dispersion shifted fibre 83(dispersion zero at 1547nm) and a polarisation controller 68. The overall loss of the loop when tuned for maximum transmission using the polarisation controller was 12.4dB. The output of the Sagnac loop was passed through a tunable 1.4nm bandpass dielectric filter 82 to remove the control pulses (at 1533.4nm) and an Erbium doped fibre amplifier (EDFA)87 to amplify the signal pulses to suitable levels for transmission (up to approximately 1mW).

The control pulses were generated using a DFB laser diode 86 which was gain switched using electrical pulses of 220ps duration and 2V amplitude direct from a 3Gbit/s bit error rate test set (BERT). This produced optical pulses with a measured duration of about 60ps and a peak power of 1.0W at 1533.4nm. These pulses were highly chirped and had a bandwidth of about 0.46nm. The pulses produced by this laser were then amplified using an EDFA 88 with a saturation output power of 8dBm and combined with the signal in the Sagnac loop using the 70% coupler 81. At low repetition rates (<20MHz), the peak output power of the pulses was approximately 700mW (launching 500mW into the loop).

The device generated output pulses at 1554nm wavelength. The peak power and duration of the output pulses could be varied by varying the pump power to the gain switched pulse amplifier thus varying the power of the gain switched pulses in the Sagnac loop. Shorter, lower power pulses could be produced by reducing the power of the gain switched pulses in the Sagnac loop and operating on the lower (pulse compressing) part of the Sagnac loop transmission characteristic. The pulse duration could be varied from 45ps to more than 100ps in this way. The pulse peak power could also be adjusted by varying the drive current to the output amplifier. Optimum transmission was observed when the device was adjusted to produce 85ps pulses with a peak power at the start of the transmission fibre of 0.4mW. The pulse form is shown in figure 12. A repetition rate of 62.5Mbit/s was used in this experiment to simplify phase locking however data with rates up to 1.2Gbit/s has been generated using this scheme - higher rates should be readily achievable.

These pulses were injected through a 30% coupler into a recirculating loop configured as shown in figure 14. The EDFA in the loop used Aluminium co-doped fibre and was pumped at 1480nm giving 25dB small signal gain and 6dBm saturation output power at 1554nm. A tunable dielectric bandpass filter with a 1.4nm bandwidth was included after the EDFA to reduce the accumulation of ASE. The fibre was 37.9km long and was dispersion shifted having a dispersion zero at 1547nm and a dispersion of 1ps(nm.km) at 1554nm. At the end of the fibre, a 10% coupler was included to permit detection of the bursts of pulses passing through the loop with a low speed receiver. The loop controller enabled a burst of

pulses to be injected into the loop which then circulated a predetermined number of times before being detected. The loop controller also controlled the frequency of the BERT synthesiser using a phase locking scheme to prevent phase drift of the received pulses. This was essential to prevent pulse wander giving increased apparent durations of received pulses. The pulses were detected using either a 1.8GHz optical receiver and a 50GHz sampling oscilloscope or a further EDFA and a 20GHz optical head in a 50GHz sampling oscilloscope.

Figure 13(a) shows the received pulses after loops (1251km) and figure 13(b) shows the received pulses after 65 loops (2464km) for a peak input pulse power (immediately after the loop amplifier) of 0.4mW. The pulse duration initially broadened from 85ps at the start to 104ps at 1251km but does not increase significantly after 1251km (if the transmission were purely linear, the pulse duration would have increased by about 30ps between 1251km and 2464km). Also included in figure 13 are the best $sech^2$ fits to these two curves. The fits are excellent indicating fundamental soliton transmission superimposed on a CW background. The peak pulse power and pulse duration at which fundamental soliton transmission is observed indicates a fibre nonlinearity of approximately 2.0 rad/(W.km) which is consistent with the nonlinearity of the fibre in the Sagnac loop gate estimated from its switching characteristics. Using the 1.8GHz optical receiver, pulses which were not visibly broadened from the (bandwidth limited) 250ps were detected up to distances of over 4000km.

Loop length, gain switched laser and amplifier requirements for unchirped pulse generator

Following are what are believed to be accurate theoretical descriptions and preferred parameters for operation of the inventive SLG according to one aspect. These should not be construed as limitative of the scope of the invention.

Length of nonlinear fibre

The phase change, $\Delta\phi$ induced in the length, L of nonlinear fibre is given by:

$\Delta\phi = k_2 P_{on3} L$ where k_2 is the cross phase modulation nonlinear coefficient of the fibre.

$P_{on\,3}$ refers to the peak power of the control pulses (ie. the pulse "on") at point 3 (see figure 8). If full switching is required, then $\Delta\phi = \pi$ hence:

$$L = \frac{\pi}{k_2 P_{on\,3}}$$

Note this assumes the duty factor, $d = \tau\, p(1)/T_{rep} << 1$. $p(1)$ is the probability of a 1 in the transmitted data and T_{rep} is the bit period. If this is not the case then:

$$L = \frac{\pi}{\quad}$$

$k_2 P_{on3}(1-d)$

If, for example, NRZ data is to be generated in this way, then the length of nonlinear fibre would have to be twice that for low duty factor RZ data.

Gain switched laser requirements

- Ideally the CW power should be much less than the pulse power ($P_{CW} \ll P_{Pulse}$). That is $P_{off1}(T_{rep} - \tau) << P_{on1}\tau$
- The pulse duration should be less than one fifth the bit period ($\tau < 0.2 T_{rep}$) . Selection of an appropriate laser will be necessary to accommodate the required bit rate.
- The peak power should be of the order of 1mW.
- The output should have low amplitude noise.
- The output should have low jitter.

Amplifier requirements

Assuming the CW power is much less than the pulse power,the CW power can be ignored and the average output power from the amplifier in the pulse can be equated with the saturation output power,P_{sat} of the amplifier (NB. this may require two amplifiers in series so that the final amplifier can be driven well into saturation):

$$P_{sat} = \frac{P_{on2}\tau p(1)}{T_{rep}}$$

$P_{on3} = k P_{on2}$ where k is the cross coupling coefficient of the control pulse coupler. We then have:

$$P_{on3} = \frac{k P_{sat} T_{rep}}{p(1)\tau}$$

giving the required length of nonlinear fibre in the loop,assuming a low duty factor d<<1, as:

$$L = \frac{\pi p(1)\tau}{k_2 k P_{sat} T_{rep}}$$

If we take $p(1) = 0.5$, $k=0.7$ and $(\tau/T_{rep}) = 0.125$ then:

$$L = \frac{0.28}{k_2 P_{sat}}$$

Taking $k_2 = 3$ radians/(W.km) (typical of standard dispersion shifted fibre) and $P_{sat} = 50$ mW = 0.05 W (possible with the best currently available 1480nm pump diode

lasers) we have $L = 1.9$km. Note that this one length will be satisfactory for a wide range of bit rates provided $P_{CW} < P_{Pulse}$ and τ/T_{rep} is a constant (≈ 0.125 in this case).

The nonlinear fibre length should preferably be as short as possible to increase stability since long Sagnac loops can be sensitive to vibration. Vibration isolation should be provided in practical embodiments of the invention, and the extinction of the loop improves as the loop length gets shorter. Improvements in fibre nonlinearity and amplifier saturation will enable further reduction of the loop length. Also, if complete switching is not required, for example because the output amplifier can compensate for the reduced power, the loop length can be still further reduced.

Dark pulses

Dark pulses are the complements of their light equivalent - ie. short periods of low light intensity and long periods of high light intensity. If such dark pulses are transform limited (ie.unchirped) and have a phase shift of π radians at the point of minimum intensity, then they can propagate as solitons in positive GVD fibre. No major benefit has been proposed for this type of transmission (indeed, the higher average power required is a drawback for amplified systems operating in saturation) however generation of such dark pulses using the inventive SLG is straightforward - it is only necessary to access the reflected signal with a circulator in the manner of figure 10 for example, or to adjust the polarisation controller for maximum transmission in the absence of a control signal.

Pulse compression

The transmission of the SLG as a function of control power is given by

$T = \sin^2[(\pi/2).(P/P_{switch}) + \phi_0]$, where ϕ_0 is a phase bias that can be varied using the polarisation controller. If the peak power of the pulses used as control pulses is very much less than the switching power $P_{peak} << P_{switch}$ and ϕ_0 is adjusted to be as close to zero as possible (ie. the device is reflective at low powers) then the transmission characteristic is such as to produce switched output pulses having durations shorter than the switching pulses. For example, if the switching pulses are approximately Gaussian in shape, then the output pulses will be shorter than the switching pulses by a factor of $\sqrt{3}$. This effect is useful in producing short pulses if the system in question is limited by the duration of the control pulses.

Soliton transmission

Soliton transmission systems overcome the dispersion limitations of conventional systems by balancing the broadening effect of dispersion on pulses with the narrowing effect of fibre nonlinearity (this requires negative group velocity dispersion (GVD) fibre)enabling long

distance, transoceanic transmission through multiple optical amplifiers. Preferred requirements for the transmitted pulses to achieve soliton conditions are:

* chirp-free (transform limited)
* ratio of pulse duration to bit period less than about 5
* wavelength and fibre chosen to give negative fibre GVD
* Average peak power over the complete link (in Watts) chosen to be approximately equal to the fundamental soliton power. This power can vary by ± 50% necessitating short links (<= 10dB loss). At 1550nm wavelength, the fundamental soliton power is given by:

$$P_1 = \frac{3.96\,|D|}{k_2\tau^2}$$

where D is the dispersion parameter in ps/(nm.km), τ is the pulse duration FWHM (full width half maximum) in ps and k_2 is the nonlinearity parameter of the fibre in radians/(W.km).

* The soliton period, z_0 should be considerably greater than the amplifier spacing. The soliton period in km (at λ_0 = 1550 nm) is given by:

$$z_0 = \frac{0.397\tau^2}{|D|}$$

Successful practical demonstrations of this technique have been performed over transoceanic distances with typical parameters as follows:

* bit rate = 2.5Gbit/s
* pulse duration = 50ps
* fibre dispersion = 1.4ps/(nm.km)
* fibre nonlinearity parameter, k_2 = 3.0radians/(W.km)

This gives P_1 = 0.74mW and requires a launched power of about 1.5mW. The soliton period, z_0 = 700 km (much greater than the amplifier spacing =40km).

The configuration given in figure 8 has produced transform limited pulses having durations of about 50ps. The wavelength of the CW signal laser and the transmission fibre can be chosen to give the required dispersion.The peak power at the output is easily amplified to about 1mW as required.

Tunable unchirped pulse source

A simple extension of the application of the invention as described above for producing unchirped pulses is to use a tunable laser as the CW optical source.This results in a wavelength tunable unchirped pulse source (such a device would enable easy tuning of the source to the correct wavelength for soliton transmission in a given system). The tunable source could be , for example,a current tunable multi-electrode laser diode, a grating

feedback external cavity tunable laser diode, a tunable single longitudinal mode Erbium fibre laser or any suitable device.

Autocorrelation using a Sagnac loop

An SLG can potentially be used as an all-fibre autocorrelator by using a coupler to split a small fraction (say 1%) of the pulse train - this is the signal and the remaining 99% is the sampling pulse train. A variable delay line scheme similar to that described previously can be used to scan the pulses through each other. If the polarisation controllers in the loop are tuned for about 45% reflection in the absence of sample pulses and the change in transmission is approximately 10%, then the transmission is approximately linear with respect to sample pulse power and the signal power transmitted is proportional to the autocorrelation function of the input pulses.

A difficulty with this technique is that since the signal and sample pulses originate from the same laser source, precautions have to be taken to prevent interference of the two.

One way to achieve this is to ensure that the signal and sample pulses are in orthogonal polarisations in the loop and on recombination at the loop coupler. Good separation of the polarisations requires polarisation maintaining fibre in the loop, a polarisation selective coupler for introducing the sample pulses into the loop and a polarisation maintaining coupler as the loop coupler.Practically it has been found that a small departure from orthogonality is sufficient to make measurements difficult.

All fibre autocorrelator

An alternative is to use the configuration of figure 8 to generate pulses having the same shape as the input pulses but a different wavelength. To ensure that the shape is the same, it is necessary to bias the SLG to half transmission (using the polarisation controller) and to operate on the nearly linear part of the transmission characteristic with $P_{control} << P_{switch}$. The cross-correlation of the signal pulses produced and the original signal pulses can now be easily determined using a delay line and another SLG. Since they originate from different sources, interference is now not a problem.

Figure 11 shows one configuration for such an autocorrelator. The first stage 79 is similar to figure 8,and produces pulses with the same shape as the pulses required to be measured, but with the wavelength of the CW source. This signal is then input to SLG 100 together with the measurement pulses.

Since the shape of the signal pulses produced is identical to the shape of the original signal pulses, the cross-correlation is the required autocorrelation of the original pulses. The average power,P_{out} of the second SLG, also biased to half transmission and with

$P_{control} << P_{switch}$ is given by:

$$P_{out} = \int_{-T_{rep}/2}^{T_{rep}/2} P(t)T(t)\,dt$$

where $T_{rep}/2$ is the repetition period, P(t)is the pulse form and T(t) is the transmission of the second SLG which is given approximately by:

$$T(t) = 0.5+kP(t+\tau)$$

where k is a constant and τ is the delay introduced between the signal and sample pulses. Substituting, we have:

$$P_{out}(t) = 0.5\int_{-T_{rep}/2}^{T_{rep}/2} P(t)\,dt + k\int_{-T_{rep}/2}^{T_{rep}/2} P(t)P(t+\tau)\,dt$$

The first term is simply a constant and the second term is the required autocorrelation function.

Use of polarisation maintaining components

The use of polarisation maintaining components offers a number of advantages to practical implementations of the SLG. Figure 9(a) shows a polarisation maintaining version of the SLG according to the present invention. In schematic form, the device is equivalent to figure 2 (b) . Input signals 96 enter coupler 93, travel around the loop 94, and are switched by control signal 99 via coupler 90 as in figure 2(a). However, coupler 93 is preferably a polarisation maintaining coupler, loop 94 is formed from polarisation maintaining fibre, and coupler 90 is a polarisation splitting coupler.

This implementation does not require a polarisation controller in the loop, and is insensitive to polarisation fluctuations caused by environmental changes. Also, the coupler which couples the control pulses into the loop can be a polarisation splitting coupler presenting only the excess loss of the coupler (typically less than 0.5dB) to the signal and the control. This is a considerable improvement on the non-polarisation maintaining device which in the example of figure 8 presents 70% or 5.2dB loss to the signal and 30% or 1.55dB loss to the control.

Industrial Applicability

There are a considerable number of variations which are possible which still lie within the scope of this general invention. The material is not limited to optical fibre. As discussed, a bulk

implementation is possible as is a guided wave on-chip implementation of the device - Indeed this type of implementation would lend itself to optical integration. The signal and sample wavelengths are widely variable limited only by fabrication technology for suitable waveguides and the availability of suitable pulsed lasers.

The device can be used for routing optical communications signals - a signal will be switched from one output to the other according to whether an optical control pulse is present or absent. If a number of such switches are combined to form a matrix switch (possibly in integrated form), this could form the basis of an asynchronous transfer mode (ATM) switch and could find application in all optical fast packet switching.

Ultra-fast, all optical logic operations can also be performed with such a device - the simplest being an optical exclusive or gate: If the control input is the result of combining two pulses having a power after coupling into the loop equal to the half switching power then the signal will be transmitted from one output if one or the other pulse is present, and from the other output if neither or both are present. The signal can be in the form of pulses - these will "clock" the device ie. measure the logic inputs at the signal pulse instant and produce the appropriate output.

The device has the further advantage that complementary outputs are generated ie. XOR and $\overline{\text{XOR}}$ in this case. Other logic gates can also be constructed.

CLAIMS

1. An optical switching device comprising an optical fibre Sagnac interferometer comprising first coupling means having an input port, an output port, an optical loop joining two other ports of said coupler, and a second coupling means intermediate the loop, the arrangement being such that a signal is produced at said output only when a signal is input having a first wavelength, and a control pulse is input to said loop through said coupling means having a second wavelength.

2. An optical switching device as claimed in claim 1, wherein the output includes means for excluding the control pulse wavelength.

3. A switching device as claimed in claim 1, wherein the first coupling means cross couples substantially 50% of the input signal.

4. A switching device as claimed in claim 1, wherein the second coupling means is located in the middle of the loop.

5. A switching device as claimed in claim 1, wherein the loop further includes means for controlling polarisation.

6. A switching device as claimed in claim 1, wherein the loop is formed from polarisation maintaining fibre.

7. A switching device as claimed in claim 6, wherein the first coupling means is of polarisation maintaining type, and the second coupling means is of polarisation splitting type.

8. An optical routing device, comprising an optical fibre Sagnac interferometer comprising first coupling means having an input port, a first output port including part of the same optical path as said input port, and a second output port, an optical loop joining two other ports of said coupling means, and a second coupling means intermediate the loop, the arrangement being such that an input signal having a first wavelength is routed to one of said output ports only when a control pulse having a second wavelength is input to said loop through said second coupling means, and the input signal is otherwise routed to the other of said output ports.

9. An optical routing device as claimed in claim 8, wherein the input port and first

output port are connected by an optical circulator such that signals input for switching by said routing device are passed to said first coupling means, and signals output by said coupling means along the same arm are routed to the output .

10. An optical routing device as claimed in claim 8 or claim 9, wherein the first and second output ports include means for excluding signals having said second wavelength.

11. An optical routing system comprising a plurality of interconnected routing devices according to claim 8.

12. An optical pulse generator comprising a first optical coupling means having an input for receiving a CW signal , an output, and a loop of optical fibre connecting two ports of the coupling means so as to form a Sagnac interferometer, said loop further including a second optical coupling means connected to a pulsed optical source , the arrangement being such that said output produces unchirped optical pulses .

13. An optical pulse generator as claimed in claim 12, wherein the CW signal has a first wavelength, and the pulsed source has a second wavelength.

14. An optical pulse generator as claimed in claim 13, wherein the output includes means for excluding the pulsed source wavelength.

15. An optical pulse generator as claimed in claim 12, wherein the output pulses are dark pulses.

16. An optical pulse generator as claimed in claim 12, wherein the CW signal is tunable.

17. An optical autocorrelator comprising:

an input for a signal pulse;

third coupling means for splitting off a part of said input signal pulse from said signal pulse,

said part being input to an optical switching device according to claim 1,

wherein the remaining signal pulse forms said control pulse, and the polarisation of said part is substantially orthogonal to the polarisation of the remaining signal pulse in the loop and at said first coupling means,

the arrangement being such that an output indicative of the autocorrelation of the

pulses is produced at the output port.

18. An optical autocorrelator comprising :

an optical pulse generator comprising a first optical coupling means having an input for receiving a CW signal , a first output, and a loop of optical fibre connecting two other ports of the coupling means so as to form a Sagnac interferometer, said loop further including a second optical coupling means connected to a sample signal , such that wavelength shifted pulses are produced by said first output with substantially the same shape but a different wavelength to the sample signal,

said wavelength shifted pulses being input to a third optical coupling means including a second output, and a loop of optical fibre connecting two ports of the third coupling means so as to form a Sagnac interferometer, said loop further including a fourth optical coupling means connected to the sample signal , such that an output is produced which is indicative of the autocorrelation of the sample signal.

Fig 1(b)

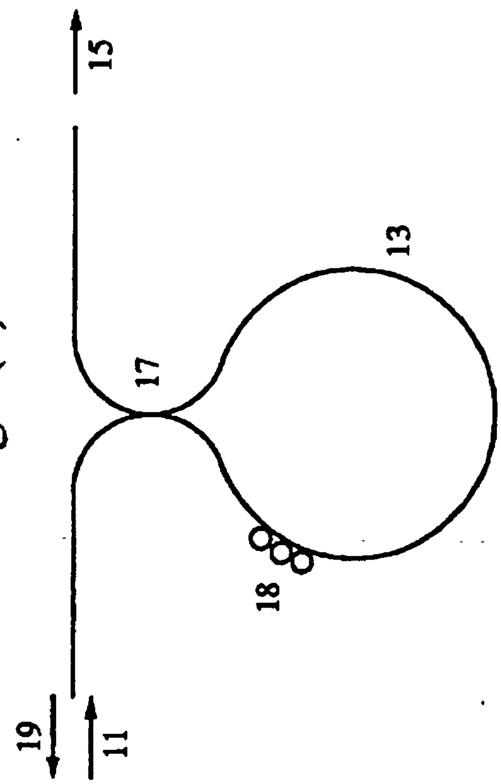
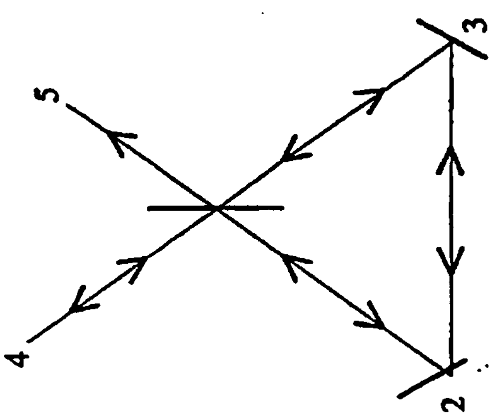


Fig 1(a)



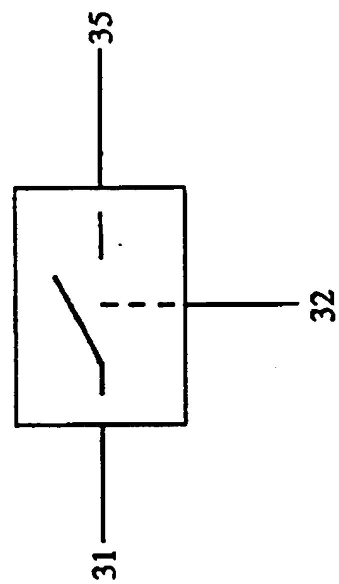


Fig 2 (b)

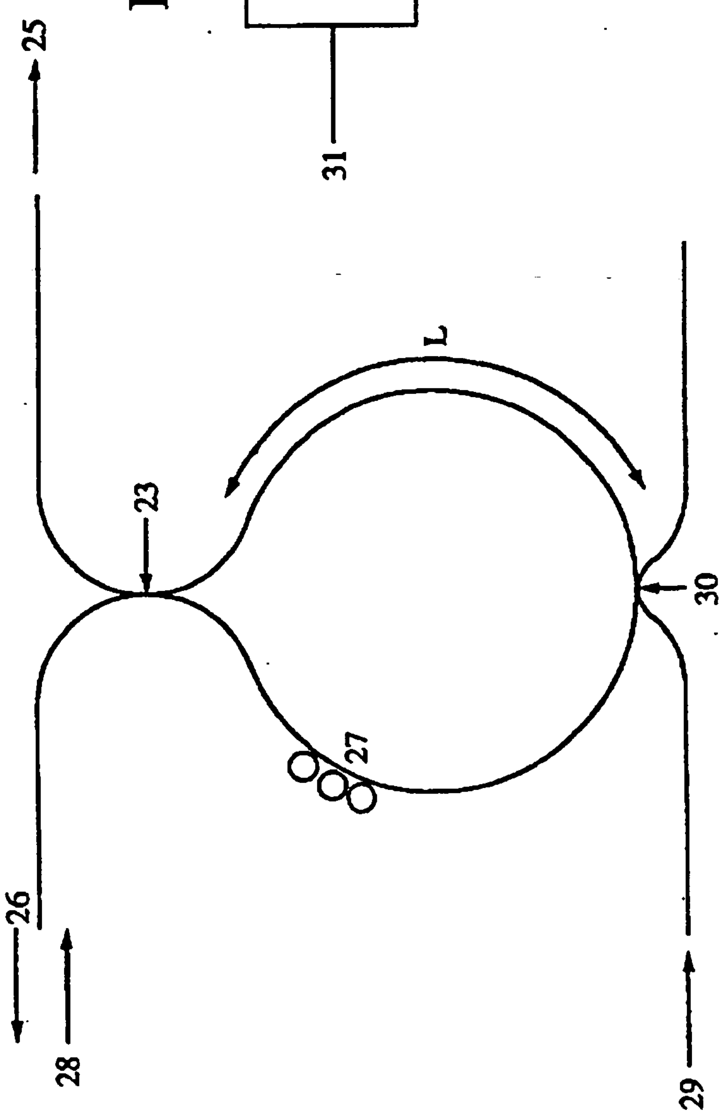


Fig 2 (a)

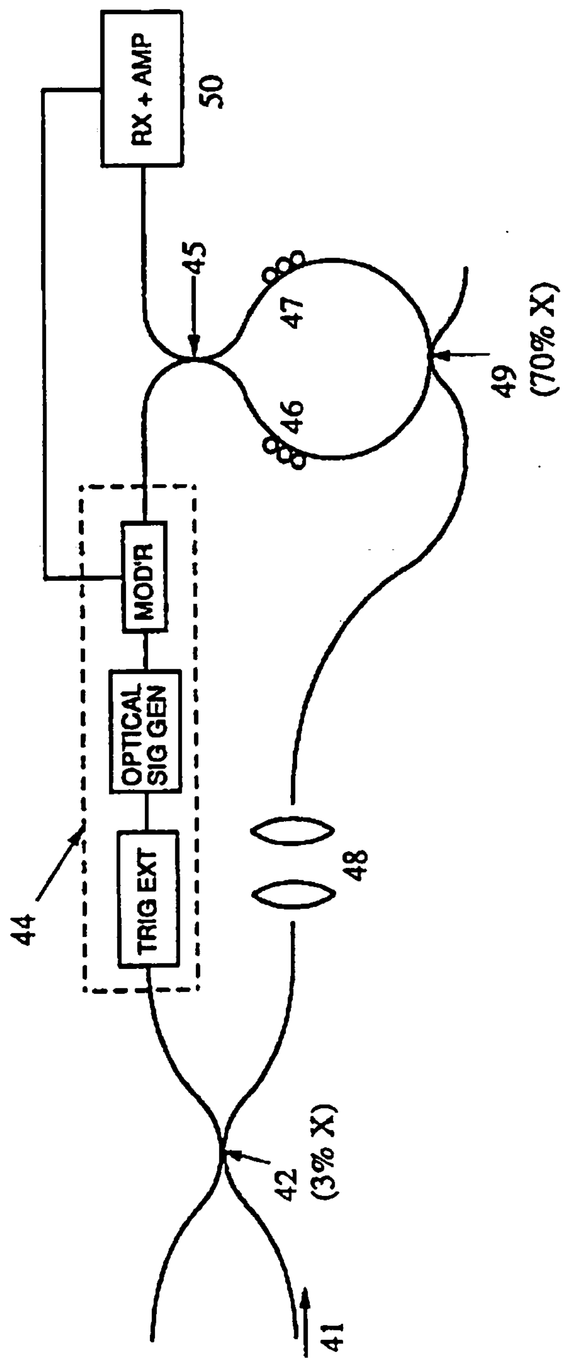
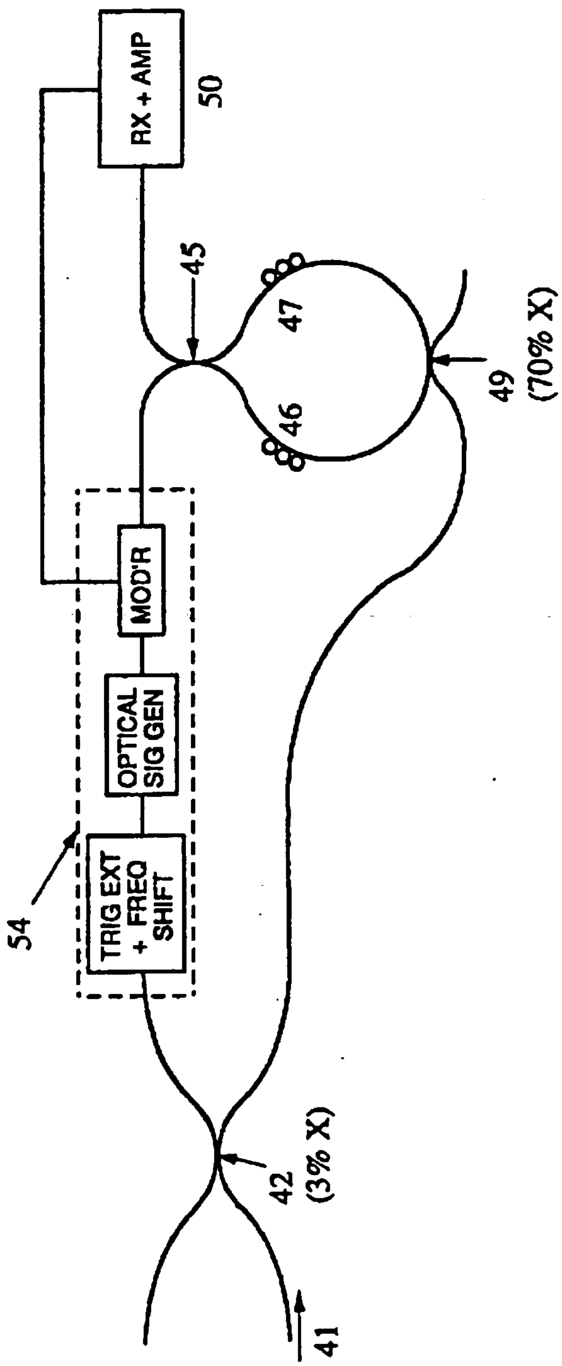

RX + AMP
50
45
47
46
49
(70% X)
MOD'R
OPTICAL
SIG GEN
TRIG EXT
44
48
42
(3% X)
41

Fig 3.

Fig 4.


RX + AMP
50
45
47
46
49
(70% X)
MOD'R
OPTICAL
SIG GEN
TRIG EXT
+ FREQ
SHIFT
54
42
(3% X)
41

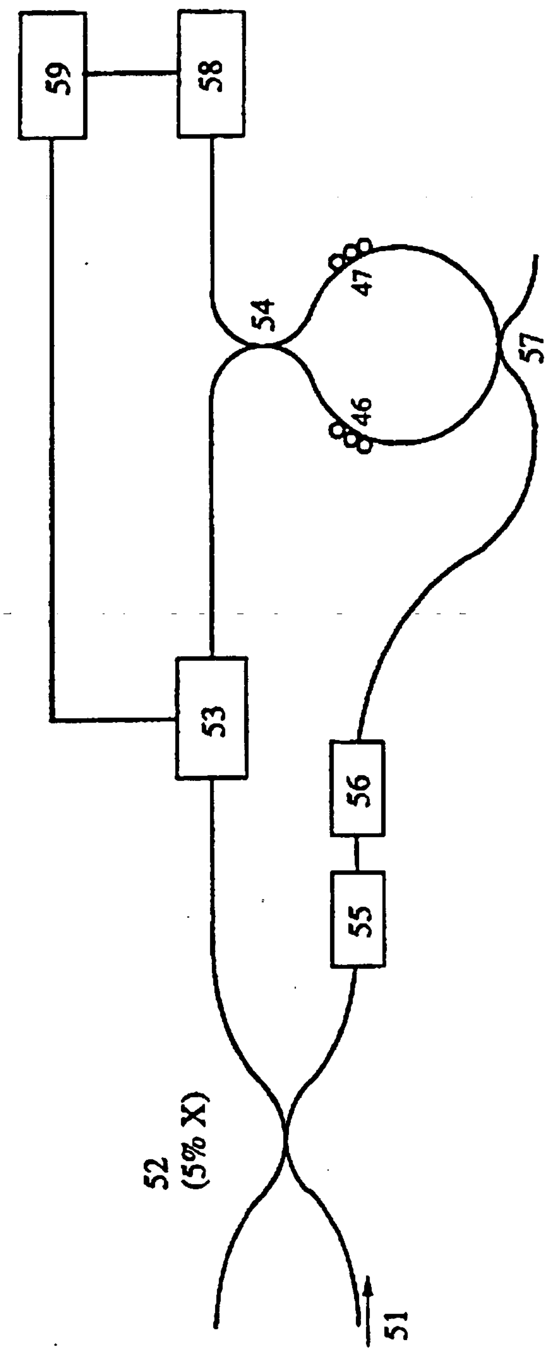


Fig 5.

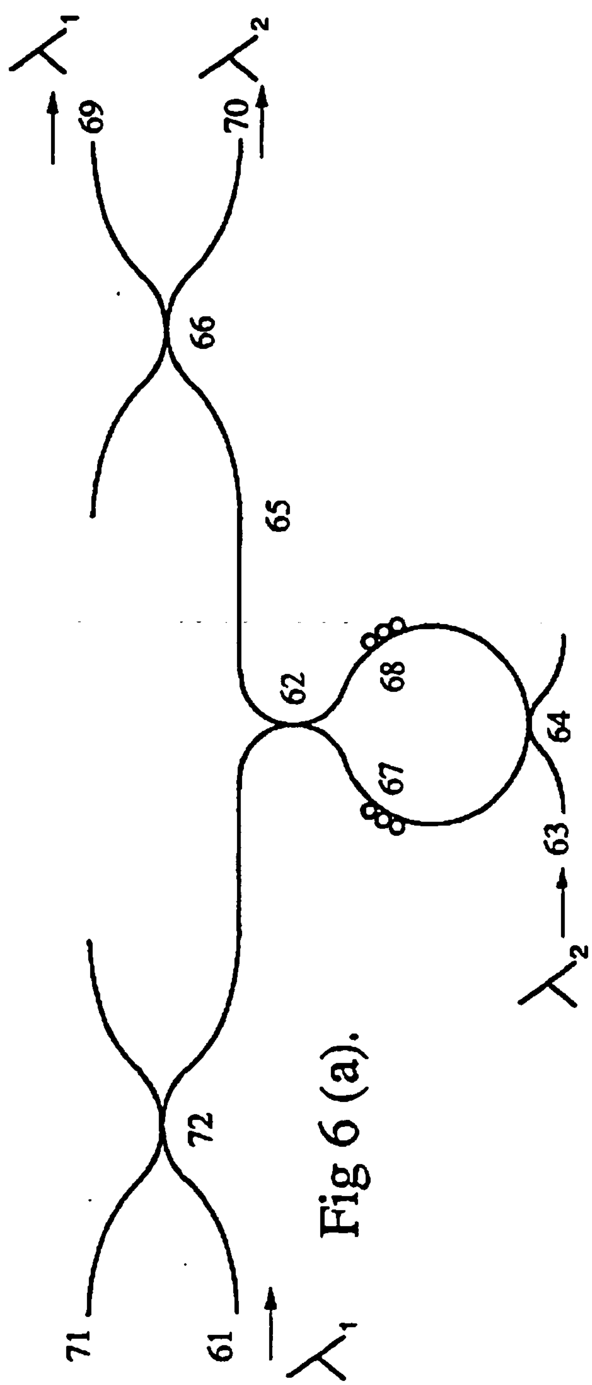


Fig 6 (a).

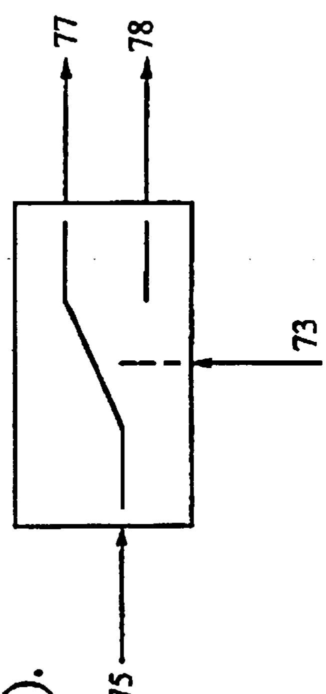
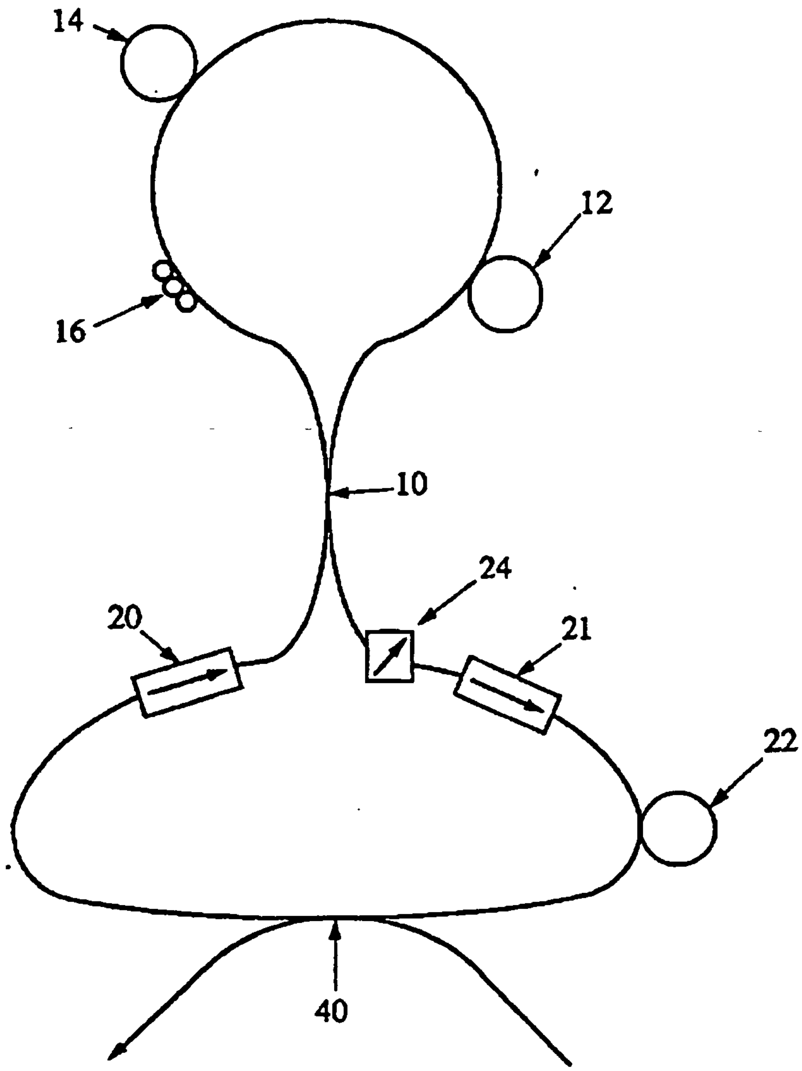


Fig 6 (b).

Fig 7.



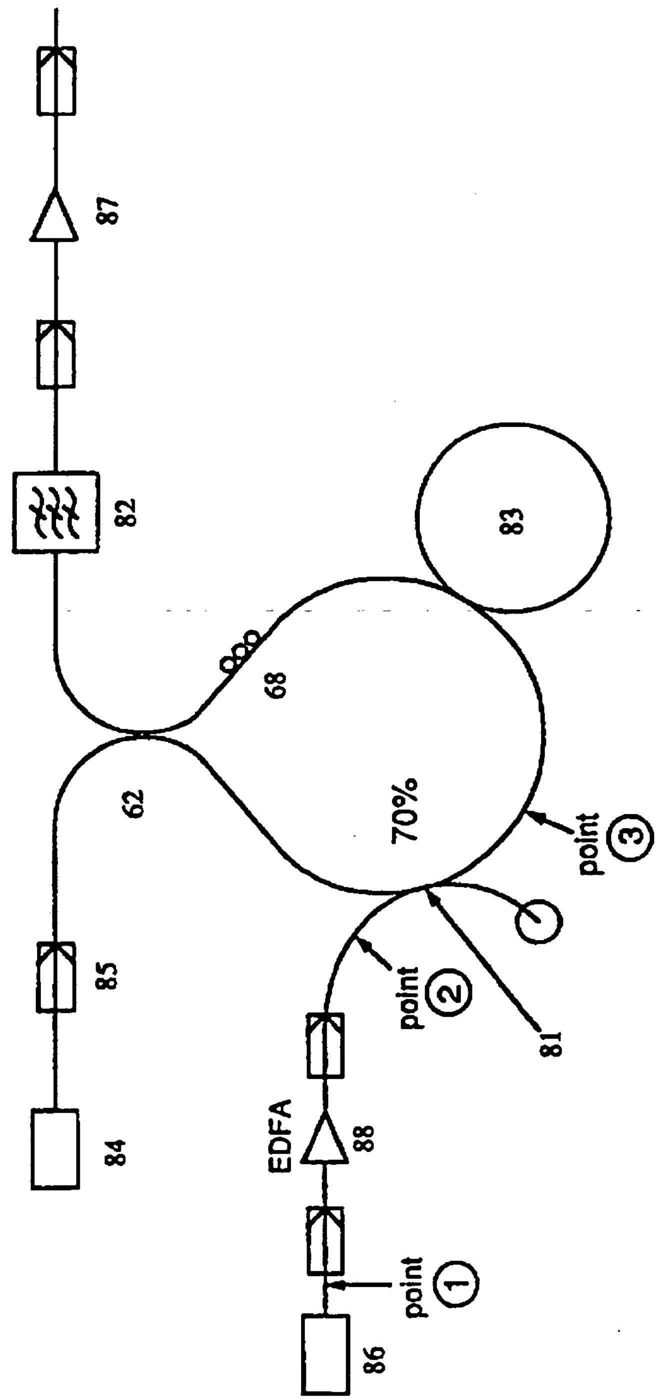


Fig 8.

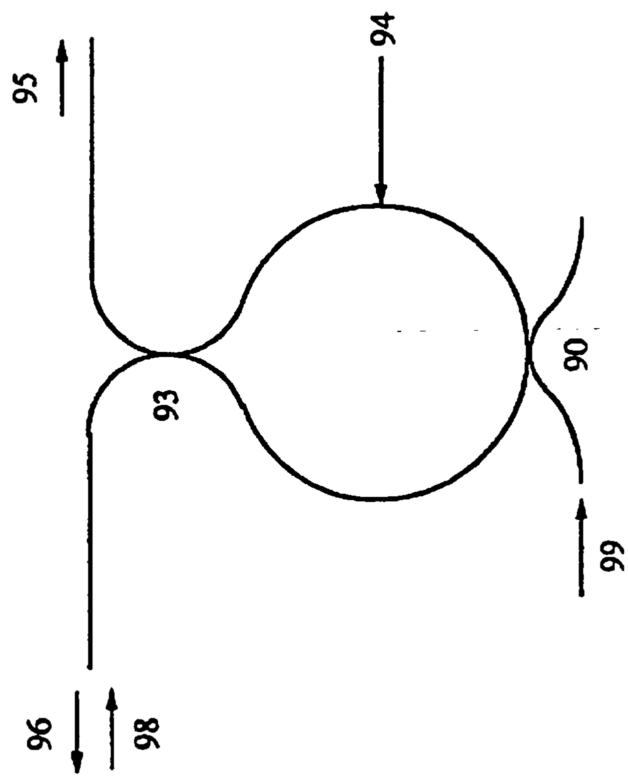


Fig 9.

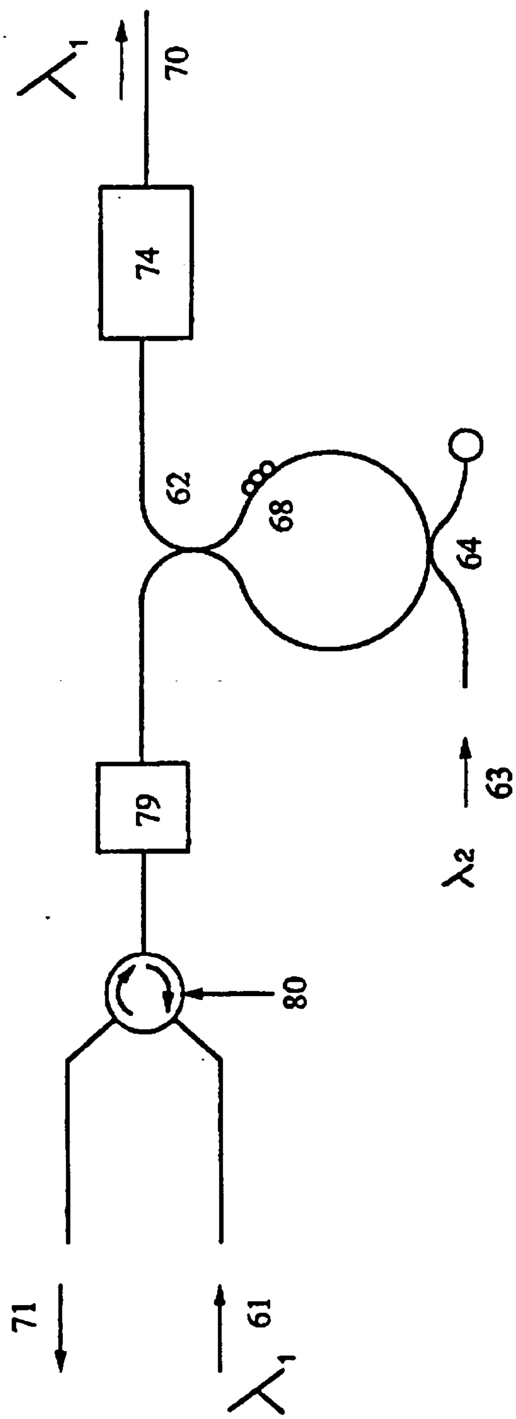


Fig 10.

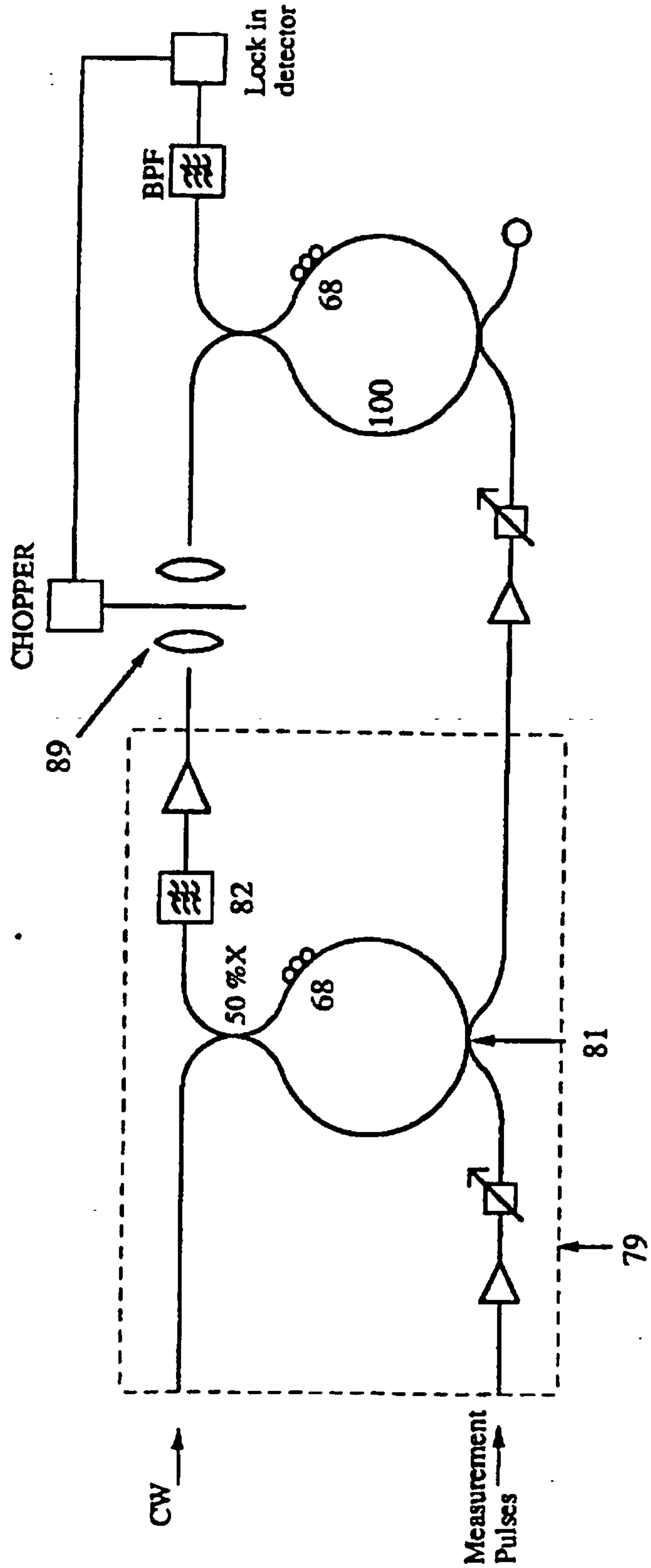

Lock in detector
BPF
68
100
CHOPPER
89
82
50 %X
68
81
79
CW
Measurement Pulses

Fig 11.

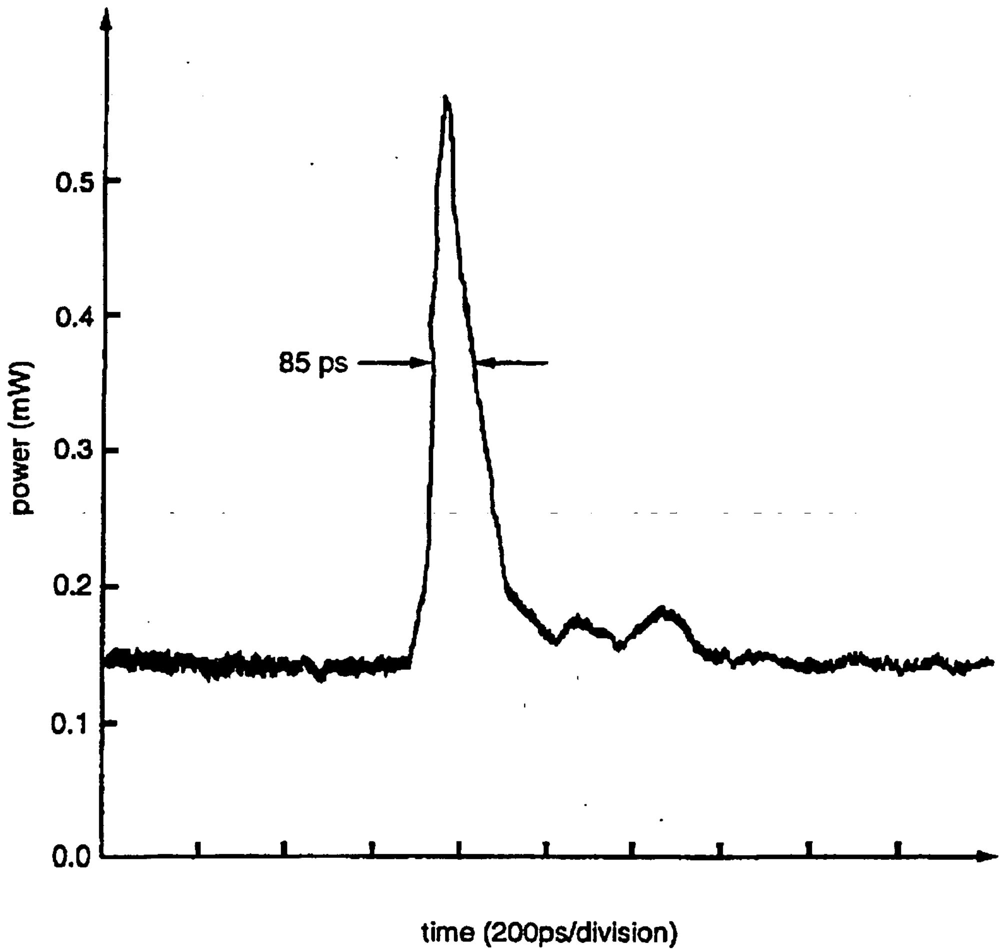
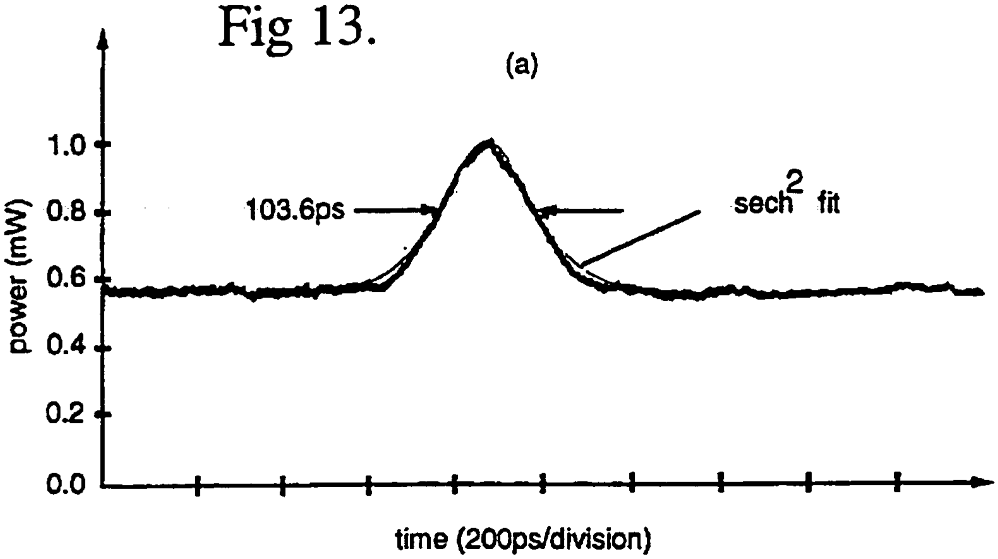


Fig 12.

Fig 13.


(a)
1.0
0.8
0.6
0.4
0.2
0.0
power (mW)
103.6ps
sech2 fit
time (200ps/division)

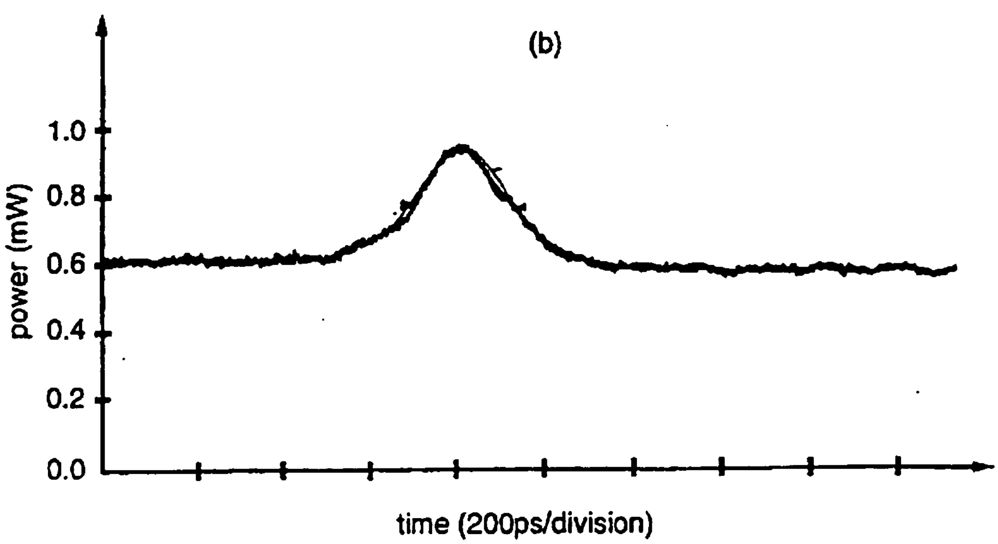
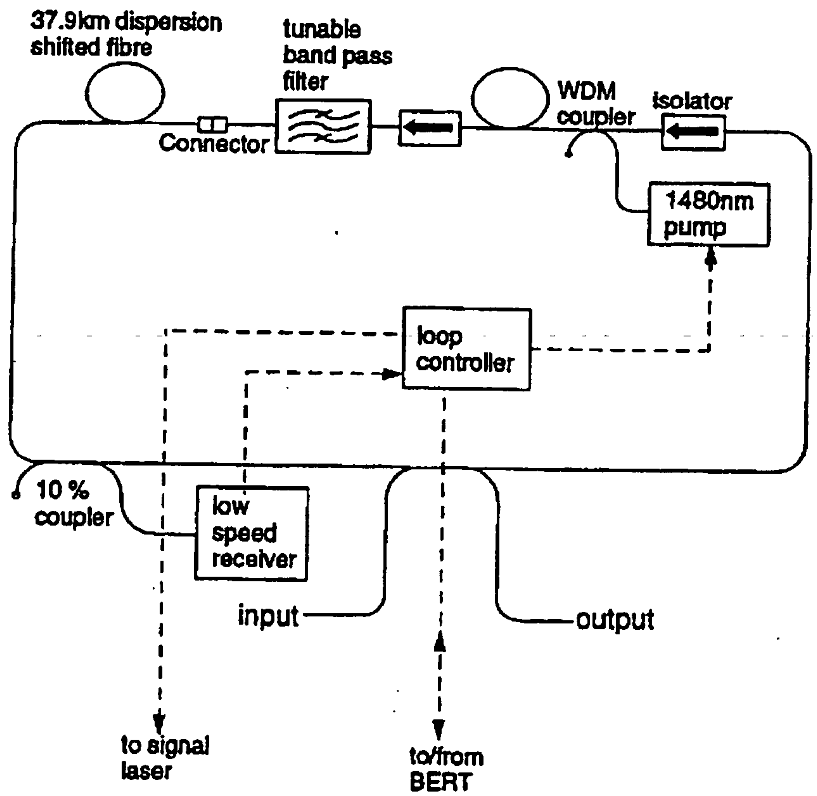

(b)
1.0
0.8
0.6
0.4
0.2
0.0
power (mW)
time (200ps/division)

Fig 14.


37.9km dispersion shifted fibre
tunable band pass filter
Connector
WDM coupler
isolator
1480nm pump
loop controller
10 % coupler
low speed receiver
input
output
to signal laser
to/from BERT

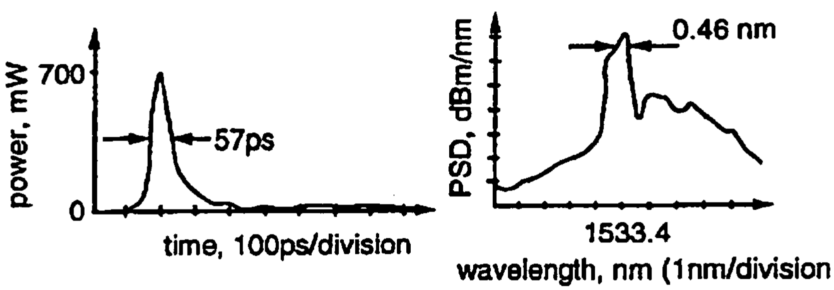

power, mW
700
0
57ps
time, 100ps/division
PSD, dBm/nm
0.46 nm
1533.4
wavelength, nm (1nm/division

Fig 15.

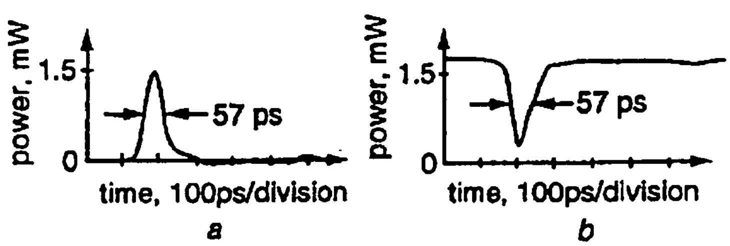
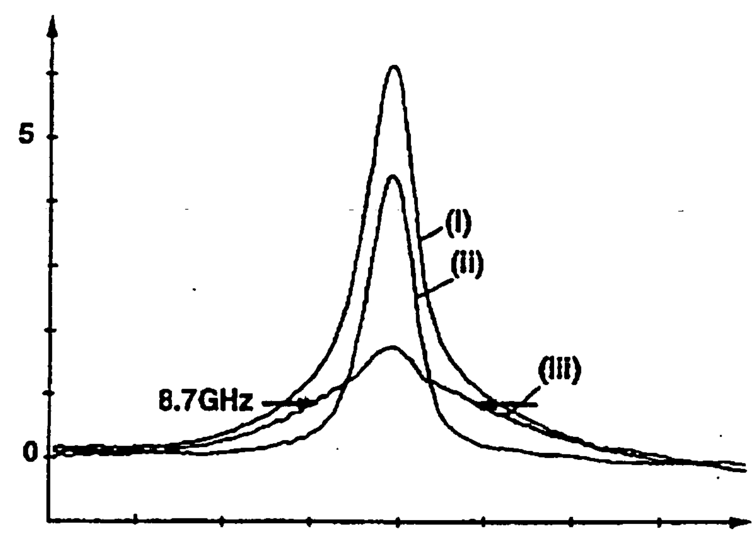

power, mW
1.5
0
57 ps
time, 100ps/division
a
power, mW
1.5
0
57 ps
time, 100ps/division
b

Fig 16.

Fig 17.



frequency, 4.48GHz/division

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.[5] G02B 6/28, G01B 9/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC : G02B 5/14, 6/28, 7/26, G01B 9/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU : IPC as above

Electronic data base consulted during the international search (name of data base, and where practicable, search terms used)
DERWENT: SAGNAC, INTERFEROMETER

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	AU,A, 67186/87 (LITTON SYSTEMS, INC.) 9 July 1987 (09.07.87) See fig 1	
A,P	US,A, 5046848 (UDD) 10 September 1991 (10.09.91)	
A,P	EP,A, 456422 (AMERICAN TELEPHONE AND TELEGRAPH CO.) 13 November 1991 (13.11.91)	
A,P	EP,A, 486766 (MESSERSCHMITT-BOLKOW-BLOHM GESELLSCHAFT MIT BESCHRANKTER HAFTUNG) 27 May 1992 (27.05.92)	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 November 1992 (18.11.92)	25 Nov 1992 (25.11.92)

Name and mailing address of the ISA/AU	Authorized officer
AUSTRALIAN PATENT OFFICE PO BOX 200 WODEN ACT 2606 AUSTRALIA Facsimile No. 06 2853929	R. TOLHURST Telephone No. (06) 2832187

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
AU	67186/87	CA	1268365	EP	231635	JP	62253239
US	5046848			NONE			
EP	456422	JP	4229836	US	5144375		
EP	486766	DE	4037118				
DD	296750	CA DD	1295876 250857	DE EP	3544265 226095	DE	3671351
							END OF ANNEX